

# **Non-contact Defect Imaging of Carbon Fiber Composites using Laser Excited Acoustic Shearography**

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## **Abstract**

The performance of carbon fiber reinforced polymer (CFRP) composites is significantly affected by the presence of subsurface defects, which originate from manufacturing processes or during operations. Although many non-destructive testing (NDT) methods have been employed to inspect CFRP materials and structures, the existing techniques are often time-consuming and sometimes require contact measurement. This paper presents a non-contact and rapid inspection method utilizing laser-excited acoustic shearography to detect subsurface defects in CFRP composites. In this method, a pulsed nanosecond laser is used to generate ultrasonic waves through thermoacoustic effect, and a shearography sensor is used to image the full-field wave-defect interactions. It is found that the proposed method can efficiently image various subsurface defect sizes in a non-contact way. The identified defects were validated through comparison with X-ray computed tomography (XCT).

**Keywords:** Carbon Fiber Composites; Acoustic shearography; Laser Ultrasonics; Non-destructive testing.

## 1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are important structural materials that are widely used in various industries owing to their high strength and low specific weight [1]. However, due to its inherent anisotropy, damage such as debonding, fiber breakage and matrix cracks usually appear when exposed to environmental factors and external loads, limiting their applications [2]. These types of damage significantly affect the mechanical strength of structures. If the occurrence of damage is not identified in time, it can lead to catastrophic failure of structures.

Currently, various non-destructive testing (NDT) methods are utilized for damage detection in composite structures, such as X-ray [3], thermography [4], ultrasound [5], and shearography [6]. X-ray computed tomography (XCT) has been utilized with high spatial resolution and has proven to be a useful tool for material characterization [7, 8]. It has been successfully employed in various studies on composite materials, allowing for accurate detection of damage [9], voids [10], and fiber orientation [11]. However, it is important to note that the use of ionizing radiation in CT requires proper safety precautions [12]. Additionally, XCT is relatively slow and there are limitations to the size of the test samples that can be rotated within an X-ray beam. Thermography is an optical NDT method that can be used to examine composite structures with access to either one or both sides [13]. This method can be divided into two types: active and passive [14], distinguished by the utilization of an external energy source. Passive thermography does not require external energy sources, whereas active thermography utilizes various heat sources, such as lasers [15], flash lamps [16], and vibrations [17]. Thermography can be used to scan large areas because it is a non-contact optical method [18]. However, this method may not provide high resolution through-thickness measurements, and its sensitivity can vary depending on the thickness of the composite structure [19].

Ultrasonic testing has been widely used for inspecting multi-layer composites [20]. It uses acoustic waves with different frequencies to identify composite structural defects such as matrix cracks [21], microbuckling [22] or delamination [23]. Over the years, more advanced ultrasonic testing methods such as phased array ultrasound testing (PAUT) [24-26] and laser ultrasonics have been developed for defect detection. The use of PAUT in composites has gained significant attention for its time-saving potential compared to that of a single ultrasonic transducer. Davide *et al* [25] experimentally investigated the fatigue plateau phase following the impact-induced delamination growth in composites. Nageswaran *et al.* [26] conducted phased array scanning of artificial defects and impact damages using C-scans and time-of-flight scans to evaluate the damage pattern. However, these ultrasonic transducers require a coupling medium between the probe and testing structure, thus limiting their applications. To overcome this limitation, non-contact laser ultrasound testing (LUT) can be employed. Song *et al.* [27] detected laser ultrasound generated waves with a microphone detection module to identify artificial subsurface defects of varying sizes in CFRPs. Ahmed *et al.* [28] inspected complex composite structures with defects using an automated laser ultrasound generator and laser vibrometer. Despite the high pin-point precision and sensitivity of laser ultrasound techniques, inspection over large areas with laser ultrasound will still require long inspection times.

Full-field imaging techniques such as shearography have become popular for detecting surface and subsurface damage in composite structures owing to their non-contact and fast imaging capabilities [29]. Shearography imaging is enabled by using various stress loading methods such as thermal [30], vacuum [31], and vibration [32] loadings. However, these common loading methods may encounter difficulties when inspecting thick composites. For example, one drawback of thermal shearography is the thermal damage caused by high surface temperatures that may exceed the safety threshold. With conventional thermal loading methods, such as flash shearography, surface temperatures may reach up to 100°C and cause

permanent damage to the surface of the sample [33]. For vacuum loading, a bulky vacuum device is required, and the scanning of large structures is challenging [31]. For the vibration loading, it requires the matching of excitation frequency and local defect resonance (LDR) for effective imaging, which is not ideal for small defects whose defect resonances are higher than the upper limit of vibration loading frequency [34].

Liu *et al.* [34] utilized the ultrasonic waves generated from a piezoelectric transducer bonded to an aluminum plate as stress loading in shearography and realized acoustic shearography which does not rely on the sweeping of ultrasonic frequency. Liu *et al.* [35] employed a multi-element piezoelectric transducer to generate directed acoustic waves within an aluminum specimen to enhance the acoustic shearography imaging of deep subsurface cracks. Zhang *et al.* [6] applied the transducer-based acoustic shearography technique for imaging of compressive damage in CFRP. Although acoustic shearography demonstrated great potentials for high resolution defect imaging, the current technique requires the use of one or multiple ultrasonic transducers to be in contact with the samples, which is not preferred in many practical applications.

This paper presents a non-contact acoustic shearography method for the defect imaging of CFRP composites. The compression tests were first conducted on CFRP samples with a centre hole to induce different damage levels. The samples were then examined using the proposed non-contact imaging method. An Nd:YAG pulsed laser was employed to produce ultrasonic waves in the samples and a shearography camera was used to capture the changes in optical patterns resulting from the wave-defect interactions. The shearography imaging results were validated by comparing the results from X-ray CT scans.

The remainder of this paper is organized as follows. Section 2 provides information on the CFRP samples with varying levels of subsurface damage produced through open-hole compression testing and provides an overview of the proposed laser acoustic shearography

system. Section 3 presents the shearography results obtained using the CFRP samples, validating through XCT results. Finally, the conclusions are summarized.

## 2. Materials and methods

### 2.1. Samples and compression tests

To investigate the performance of the proposed laser acoustic shearography system, 15 open hole CFRP samples were loaded with increasing compression loads to generate defects such as delamination and fiber breakages at varying extents. The samples were manufactured and provided by Hexcel Composites Ltd. (UK) with a fiber orientation of  $[0^\circ/45^\circ/-45^\circ/90^\circ]_{4S}$ . Each sample was prepared according to the open hole compressive standard test method ASTM-D6484, with the dimensions of 300 mm x 36 mm x 4 mm and a hole diameter of 6 mm, as shown in Fig. 1 (a).

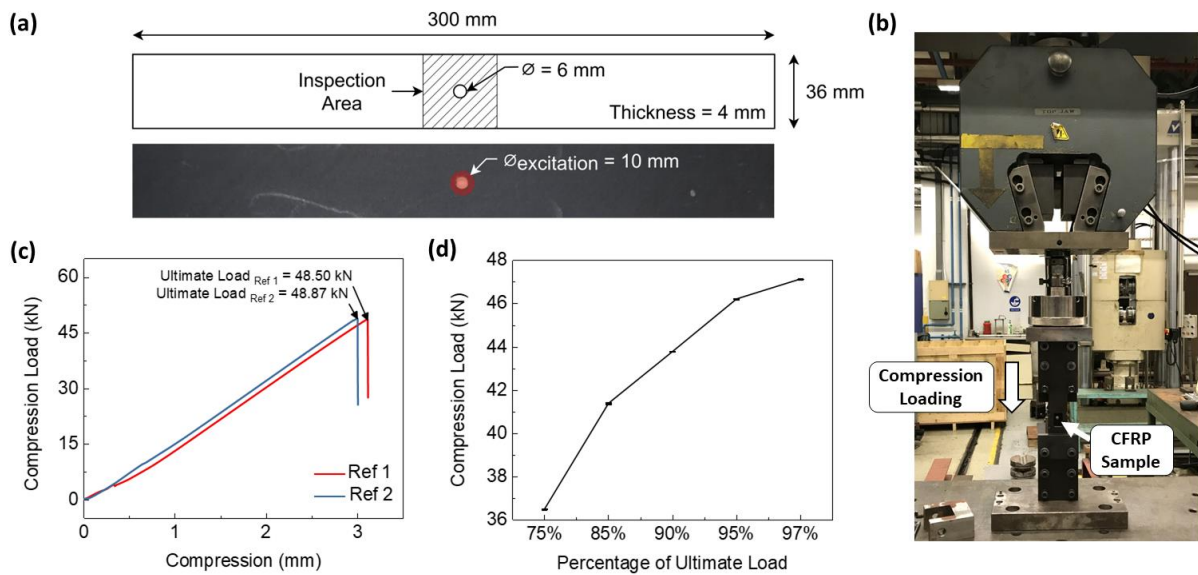


**Fig. 1.** (a) Composite specimen with drilled hole prepared in accordance with ASTM D6484, (b) open-hole compression test setup, (c) loading curve for reference samples yielded to the ultimate compressive load and (d) loading profile of samples with different load points from 85% to 97% of ultimate compressive load.

To create samples with varying defect levels, axial compression tests were performed on the samples, as depicted in Fig. 1 (b). Initially, a reference test was carried out to determine the ultimate compressive loads of the composite samples and the samples were loaded to complete failure. The load-displacement curves for the two reference samples are shown in Fig. 1 (c). It was determined that the average ultimate compressive load for these two specimens was 48.7 kN. Subsequently, further compression tests were carried out on identical composite samples that were loaded onto different stress levels, where the defects were subsurface and not visible along the surface of the composites. Each sample was assigned a % value (i.e., 85%, 90%, 95%, and 97%) corresponding to the percentage to the ultimate compressive load as illustrated in Fig. 1 (d).

## 2.2. Laser excited acoustic shearography

Fig. 2 shows the overall configuration of the proposed non-contact laser excited acoustic shearography system. An Nd: YAG laser was used for ultrasonic wave generation, and a shearography camera was employed for the full-field measurement of the out-of-plane surface displacement gradient caused by the ultrasonic excitation. When a laser pulse irradiates the sample surface, it absorbs the radiation energy, leading to a sudden temperature change near the irradiated area. This temperature variation generates transient elastic waves due to thermoacoustic effect. The wavelength of the elastic waves generated by a laser beam is dependent on the laser beam size when the pulse duration of the laser beam is sufficiently short. In this study, the laser beam was assumed to exhibit a Gaussian distribution. Considering the heat equation and ultrasonic wave equation, the thermal conduction can be expressed as [36, 37]

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) + Q \quad (1)$$

$$\mu \nabla^2 \mathbf{w} + (\lambda + \mu) \nabla (\nabla \cdot \mathbf{w}) = \rho \frac{\partial^2 \mathbf{w}}{\partial t^2} + \alpha (3\lambda + 2\mu) \nabla T \quad (2)$$

where  $\rho$  is the material density,  $C$  represents the specific heat capacity of the material at contact pressure,  $T$  is the temperature rise in the material at time,  $t$ ,  $K$  denotes thermal conduction coefficient,  $\alpha$  is the linear thermal expansion coefficient and  $Q$  is the power density of the heat source generated by laser source irradiation.  $\lambda$  and  $\mu$  are the Lamé constants,  $\mathbf{u}$  represents the displacement vector due to the thermoelastic effect. The laser beam is assumed to be completely absorbed at the surface in a small volume due to strong skin effect of the materials. Thus, a heat source,  $Q$ , ignoring the optical penetration of the incident laser beam is given by:

$$Q = I_0(1 - R)f(x)g(t) \quad (3)$$

where  $I_0$  denotes the peak power density of incident laser source,  $R$  is the reflection coefficient of the specimen surface.  $f(x)$  and  $g(t)$  are the spatial and temporal distribution of the incident laser source, respectively and can be expressed as

$$f(x) = \exp\left(-\frac{r^2}{r_0^2}\right) \quad (4)$$

$$g(t) = \frac{t}{\tau} \exp\left(-\frac{t}{\tau}\right) \quad (5)$$

where  $x_l$  is the position of the laser source center,  $w_0$  represents the width of incident laser line source,  $a_0$  denotes the laser pulse rise time, and  $t_0$  is the pulse duration.

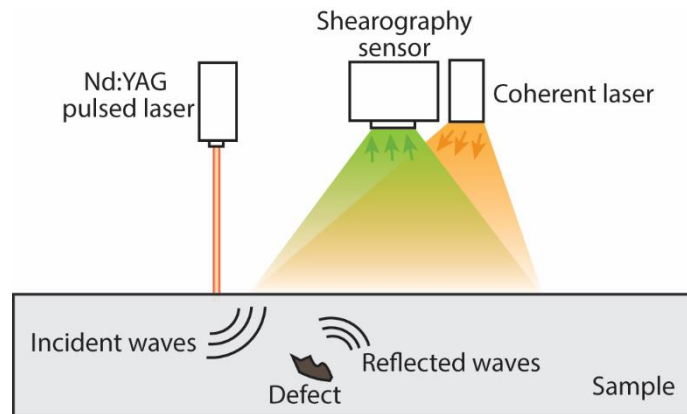


**Fig. 2.** Overview of the proposed non-contact laser acoustic shearography system. An Nd:YAG pulsed laser is employed to produce ultrasonic waves on the sample, with its exposed surface being illuminated by a coherent laser. The shearography sensor captures the speckle interferogram resulting from the interaction of the waves and defects using the phase shifting method.

Phase shifting shearography is based on the subtraction of two phase reconstructed images obtained when the test material is under two different stress states [38]. A coherent laser light source is used to illuminate the sample surface and a shearing mirror is used to interfere with the scattered light from neighboring points on the surface to produce a speckle interferogram. The optical speckle interferogram contains surface information of the test sample. When the sample is subjected to mechanical stress loading, the corresponding speckle interferogram is changed because of the surface deformation. By subtracting the phase images in two stress states, the surface deformation gradient and phase information along the shearing direction can be derived. Thus, the subsurface defects which cause changes in surface deformation can be imaged in shearography camera.

The relative phase difference between reference and loading state can be expressed as :

$$\delta\phi = \phi' - \phi \quad (6)$$

where  $\phi'$  denotes the optical phase at reference state and  $\phi$  denotes the optical phase when mechanical loading is applied.  $\delta\phi$  represents the relative phase difference between the two stress states. The shearography camera was positioned perpendicular to the sample and the shearing direction was used to calculate the out-of-plane displacement derivative (i.e.,  $\partial w / \partial x$ ). The relative phase difference can be written as:

$$\delta\phi = \frac{4\pi}{\lambda_L} \frac{\partial w}{\partial x} \delta x \quad (7)$$

where  $\lambda_L$  is the wavelength of the laser diode and  $\delta x$  is the shearing distance. Based on Eqs. (6), and (7),  $\delta\phi$  can be retrieved pixel-by-pixel, producing a phase map corresponding to the reference status, and then,  $\partial w/\partial x$  can then be evaluated.

### **2.3. Non-contact shearography imaging of surface defects**

The experimental setup for the laser excited acoustic shearography system is depicted in Fig. 3. An Nd:YAG pulsed laser with wavelength of 1064 nm, pulse duration of 12 ns, pulse repetition rate of 20 Hz, and 0-90 mJ pulse energy output, was used to generate ultrasonic waves in test materials. The pulsed laser beam was expanded to 10 mm to irradiate the surface of the sample. To create an interferometry pattern with the shearography optics, a laser light with a wavelength of 660 nm was beam expanded for coherent illumination and the shear distance of the shear mirror was adjusted to 0.8 mm. A shearography sensor consisting of a 5-Megapixel monochrome camera with a frame rate of 9 Hz at full resolution was used to capture the reference and ultrasonic loaded interferometry patterns. The camera lens used in the setup was a Tamron 17-50mm f/2.8 XR Di II lens with an aperture of f/2.8 and the exposure time of the camera was set to 19.2 ms. In this study, the shearography sensor used was an SE2 sensor (isi-sys GmbH, Germany). The field of view (FOV) of the camera was configured to  $45 \times 38$  mm<sup>2</sup> and positioned 235 mm from the shearography camera. The experiments were carried out with various laser pulse energy, from 6 mJ to 40 mJ.

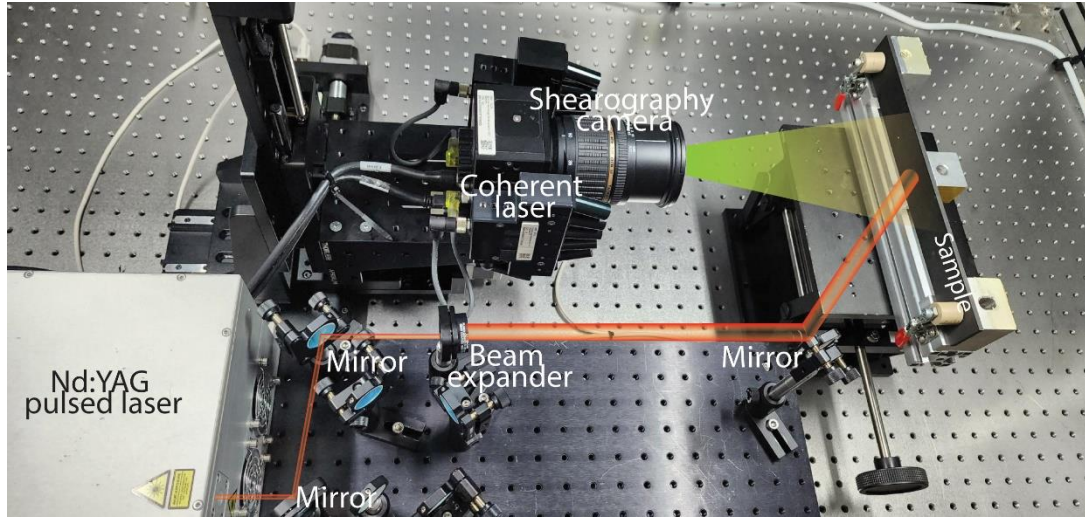


**Fig. 3.** Experimental laser excited acoustic shearography system for imaging subsurface defects in CFRP.

Due to the broadband ultrasonic wave excitation of the pulsed laser, coherent laser lights were set to operate in the continuous wave mode. A real-time phase reconstruction function was used to process the phase difference in the interferograms. In this measurement mode, five interferograms across a phase range of  $2\pi$  were first captured to obtain the reference phase image,  $\phi$ . Thereafter, five subsequent loaded interferograms were continuously updated to reconstruct a loaded phase image,  $\phi'$ . The resulting image was processed in real-time by calculating the relative phase difference,  $\delta\phi = \phi' - \phi$ .

### 3. Results and discussions

#### 3.1. Acoustic shearography imaging results

Fig. 4 shows the shearography experimental results of a composite sample which underwent 97% of ultimate compressive load. In the absence of ultrasonic excitations, the shearography image seen in Fig. 4(a) shows a reference unloaded image with no defect features. After the excitation pulsed laser is turned on, the subsurface defect features are revealed by the shearography camera, as shown in in Fig. 4(b) to (h). Fig. 4(b) to (h) are shearography images with increased laser pulse energy, from 6 mJ to 12 mJ. It is evident that

the phase difference in the shearography images increases with the higher laser pulse energy. This can be correlated to the stronger ultrasonic waves generated by the pulsed laser. A deformation covering the whole irradiation area was also observed for laser pulse energy more than 17 mJ.

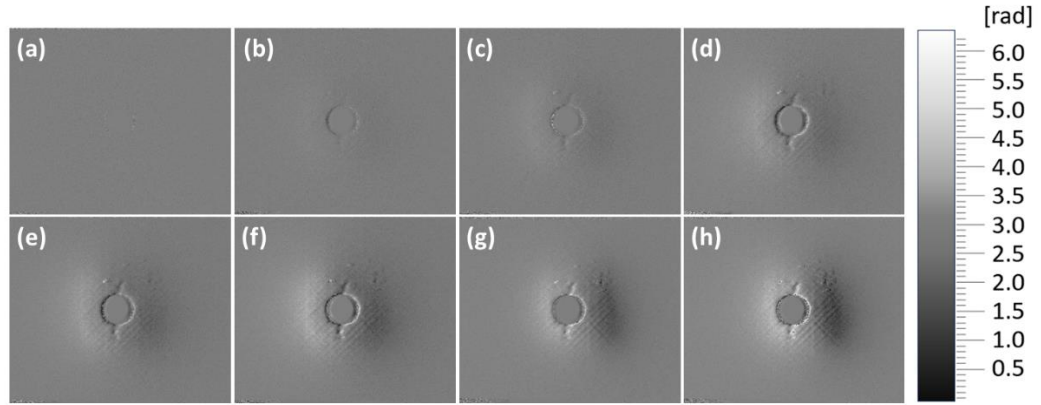


**Fig. 4.** Shearography results with increasing pulsed laser energy (a) 0 mJ (b) 6 mJ, (c) 12 mJ, (d) 17 mJ, (e) 23 mJ, (f) 29 mJ, (g) 35 mJ and (h) 40 mJ.

While a higher laser pulse energy is preferred to increase the phase difference of defects, it may also result in an increase in noise that envelops the defect. Based on the experimental parameters and conditions, the optimal laser energy output of 29 mJ was determined as the phase difference image of the CFRP sample with the highest compression damage reaches near 0 and  $2\pi$ , as seen in Fig. 4(f) and Fig. 5(a). Thus, the laser pulse energy was fixed at 29 mJ for subsequent shearography tests with the remaining samples.

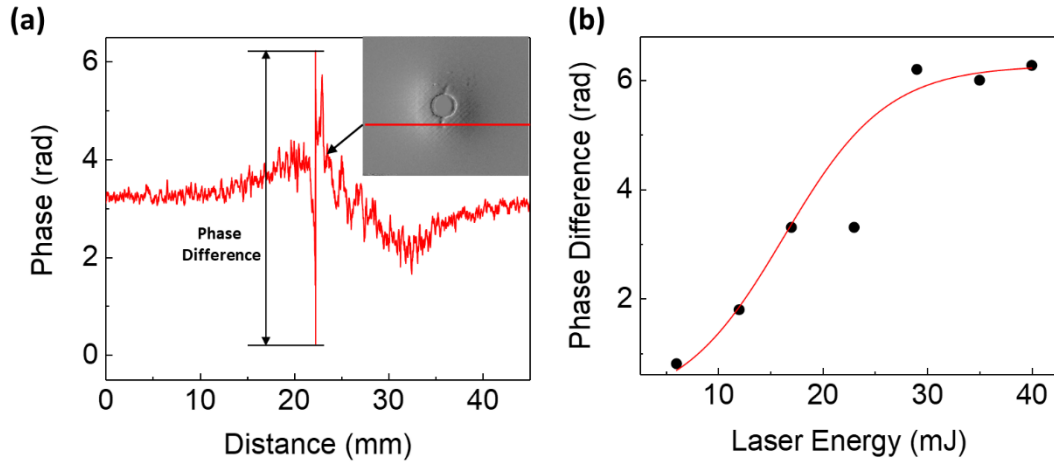


**Fig. 5.** (a) Phase profile of Fig. 4(g), and (b) Phase difference of Fig. 4 with varying laser pulse energy output.

Fig. 6 shows the shearography imaging results of samples which underwent 85% to 95% of the ultimate compressive load. As shown in Fig.6(a)-(d), there are no obvious defects around the open hole of the composite samples viewed by naked eyes. However, the defect features can be clearly visualized in the corresponding shearography images in Fig.6(e)-(h). A defect evolution process can be seen with the increase of the loads. The first major defect can be observed in the sample with 90% ultimate load (Fig.6(f)). With the increase of compressive load to 95% and 97%, two major defects appear on the opposite side of the open hole as shown in Fig. 6(g) and Fig.6(h), respectively.

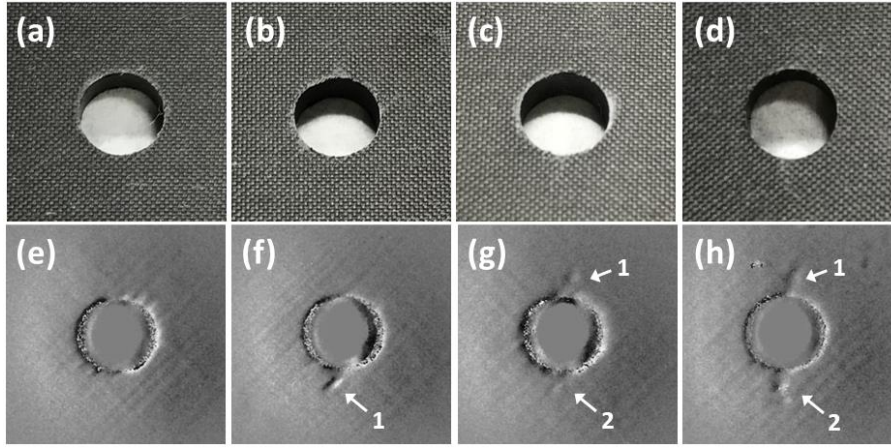


**Fig. 6.** Optical image of samples with (a) 85%, (b) 90%, (c) 95%, and (d) 97% ultimate compressive load. Laser excited shearography images of samples with (e) 85%, (f) 90%, (g) 95%, and (h) 97% of ultimate compressive load.

### 3.2. Validation with X-Ray Computed Tomography

To validate the defects found in the shearography images as shown in Fig. 6, XCT scans were conducted using a Nikon XT H 225 CT system to produce the XCT images. A total of 256 cross-sectional images were scanned and processed. Fig. 7 shows the comparison of shearography images and XCT images for the four composite samples. It is evident that shearography images have captured the main features of the defects in the four samples, as compared to the corresponding XCT images. A detailed comparison of the XCT and shearography results of the sample yielded to 97% ultimate compressive load is shown in Fig.8. Fig. 8 (a) and (b) show the subsurface damage within the composite laminate layers captured by XCT, which validates the optical images shown in Fig. 8(c). In Fig. 8 (b) and (c), the longest defect measured from the XCT scan is 2.24 mm, whereas the length of the same defect imaged by the shearography camera is 2.02 mm. The defect length measured using the laser excited acoustic shearography technique is 9.83% shorter than the one measured in the XCT scan. However, the shearography images were acquired in a short span of around 10 seconds while the XCT scan takes a few hours. This shows that the laser excited acoustic shearography

technique can be a fast and non-contact inspection method with reasonable accuracy for composite characterizations.

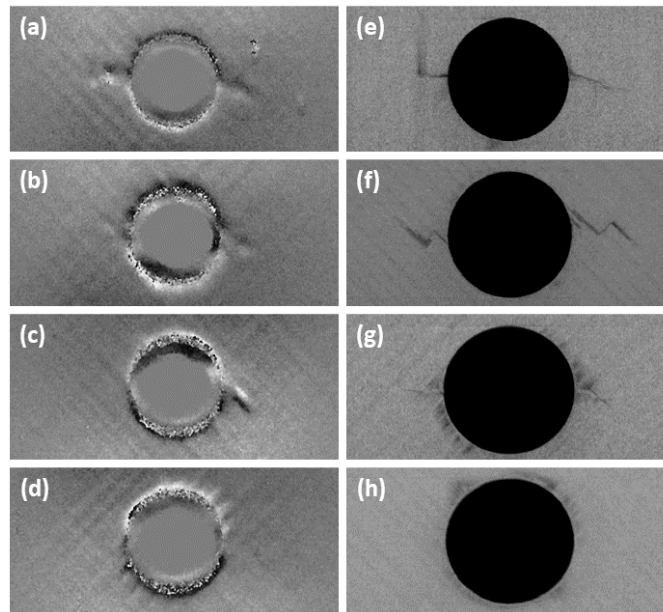


**Fig. 7.** (a) Laser excited shearography images of samples with (a) 85%, (b) 90%, (c) 95%, and (d) 97% ultimate compressive load. (e) XCT images of samples with (e) 85%, (f) 90%, (g) 95%, and (h) 97% ultimate compressive load.

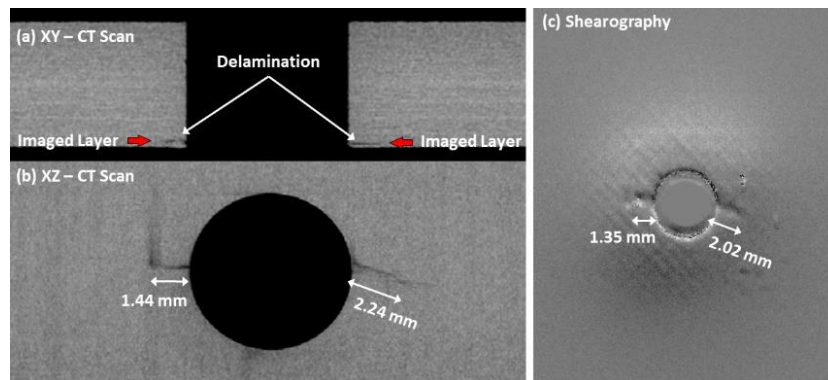


**Fig. 8.** (a) CT scan view from XY orientation, (b) CT scan view from XZ orientation and (c) laser excited acoustic shearography image of sample with 97% of ultimate compressive load.

#### 4. Conclusions

In this paper, a non-contact full-field imaging system based on laser excited acoustic shearography consisting of a nanosecond pulsed laser and shearography camera was developed

to detect subsurface defects in CFRP composites. The nanosecond pulsed laser was used to generate ultrasonic waves in composite materials and the shearography camera was used to image the wave-defect interactions. Composite samples with varying levels of compressive damage were prepared and the subsurface defects were imaged by the non-contact laser excited acoustic shearography system. The laser acoustic shearography system yielded results closely matching those obtained by XCT, demonstrating an accuracy of over 90% in defect length determination, within a few seconds of inspection time. This shows that laser excited acoustic shearography is a promising technique for non-contact high speed defect imaging in composite materials.

### **CRedit Author Statement**

**Zi Wen Tham:** Investigation, Experiments, Writing - Original Draft. **Santhakumar Sampath:** Methodology, Investigation, Writing - Review & Editing. **Yi Fan Chen:** Investigation. **Bisma Mutiargo,** Investigation. **Lei Zhang:** Conceptualization, Writing - Review & Editing.

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